perimental procedures primarily by eliminating the slow coincidence requirement of 5-sec-filtered data. However, from our understanding of Weber's results, the slow filter does not appear to eliminate a substantial fraction of events detected by the fast-coincidence circuitry. Our experiment suggests that (a) Weber's events[2] of 1969–1970 were not produced by gravity waves, (b) an intense source or sources of gravity waves active in 1969–1970 is less active in 1973, or (c) the duration of these gravity waves is $\gg 24$ msec.

No doubt it will be possible for Weber or others to model the experiment more completely than we have done. It would be even better if the individual bars of Weber's apparatus were provided with electrostatic calibrators which could be pulsed simultaneously in order to produce excitations of known energy which would then be sought in a blind fashion by the computer analysis as if they were gravity waves. Table I of Ref. 1 contains such data for our single bar, which provides an unambiguous determination of the efficiency of our experiment to detect gravity waves depositing various energies in the bar.

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Lower Bound on the Intermediate-Boson Mass*

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We report a search for the W boson via the production process $\nu_\mu + Z \to W^+ + \mu^- + Z$ and decay process $W^+ \to \mu^+ + \nu_\mu$. We have set a firm lower bound on the mass of the W boson as a function of the branching fraction into leptons $[B = (W \to l + \nu)/(W \to \text{all})]$. For example, we have determined that $M_W > 4.4$ GeV/c^2 (90% confidence limit) for $B = 0.5$.

It is well known that the ordinary four-fermion theory of the weak interaction predicts incorrect behavior at high energies. In particular, it is easily shown that the theory predicts a total neutrino cross section on pointlike particles that grows linearly with laboratory energy ($\sigma_F \propto G^2 E_{\text{lab}}$). This rising cross section eventually violates the s-wave unitarity bound at $E_{\text{lab}} \sim 10^5$ GeV.

One possible modification to this weak-interaction theory is to introduce an intermediate spin-1 particle, the W boson, which mediates the interaction.[1] Its propagator term $G \to G/(1+q^2/M_W^2)$ serves to damp the cross section at large q^2 (four-momentum transfers). This retains the correct low-energy behavior, but now yields a total neutrino cross section that asymptotically grows logarithmically $[\sigma \propto \ln(2M_p E_{\text{lab}}/M_W^2)]$. This does not completely solve the theoretical difficulties, and more than just the addition of a single spin-1 boson is needed to obtain a finite theory of the weak interaction.

Estimates of the W-boson mass are model dependent and vary widely. For example, the cutoff energies calculated from second-order processes like the K_L-K_S mass difference and the $K_L \to \mu^+ + \mu^-$ rate are 3–15 GeV,[2] while theories that unify the weak and electromagnetic interactions yield $M_W \sim 37$ GeV.[3]

Experimentally, W bosons could be produced by hadrons, muons, or neutrinos. At present, there is no positive evidence for the existence of W bosons, although there have been several searches.

In hadron collisions, the process

$$p + Z \to W^\pm + \text{hadrons}, \quad W^\pm \to \mu^\pm + \nu$$

was searched for at the Brookhaven alternating gradient synchrotron.[4] An upper limit $\sigma_W B' \leq 6\times 10^{-36}$ cm^2 for M_W between 2.0 and 4.5 GeV/c^2 was obtained for this process $[B'=(W\to\mu\nu)/(W\to\text{all})]$. However, uncertainties in the production cross section for W bosons make it difficult to conclude that a firm lower bound was set.

Experiments attempting to produce W bosons directly with neutrino beams have been carried out both at Brookhaven and CERN.[5] The production process

$$\nu_\mu + Z \to W^+ + \mu^- + Z,$$

with decay modes

$$W^+ \to \begin{cases} \mu^+ + \nu_\mu \\ e^+ + \nu_e \end{cases}$$
$$\to \text{hadrons},$$

has been searched for. In this case, production cross sections and distributions of the final products can be reliably calculated. The W boson decays promptly ($\Gamma > 10^{18}$ sec^{-1}), but there is no reliable estimate of the leptonic-to-hadronic branching ratio. Neutrino experiments looking for all three decay modes have been carried out, and firm lower limits of $M_W \gtrsim 2$ GeV/c^2 have been set.[5]

We report here the initial results from a new neutrino experiment, which uses counter–spark-chamber techniques, and is set up at the National Accelerator Laboratory (NAL) in Batavia, Illinois. As a first task, we have searched for directly produced W bosons which decay by the mode $W^+ \to \mu^+ + \nu_\mu$.

Our experiment differs from previous experiments in that we use a dichromatic rather than a broad-band neutrino beam. The beam has little low-energy neutrino and antineutrino background. This eliminates a potentially serious problem when searching for events where most of the final-state energy cannot be observed or where positively charged leptons are expected to be produced. Both of these are true in W production: The μ^+ from W decay is one of the unique signatures of the event, and the final-state neutrino typically carries away over half of the energy.

To produce the neutrino beam, the primary 300-GeV NAL proton beam was targeted 975 m upstream from our detection apparatus. The secondary hadrons were momentum selected at 160 GeV with a momentum bite of $\pm 11\%$, focused into a parallel beam, and directed toward our apparatus into a 345-m decay tunnel followed by 530 m of earth and iron shielding. For the 160-GeV hadron beam, the mean neutrino energies in our apparatus for $K\to\mu\nu$ decays are 145 GeV, and for $\pi\to\mu\nu$ decays are 50 GeV.

The apparatus consists of a 170-ton target detector, followed by an iron-core toroidal magnet. The relevant information for analyzing an event are the muon momentum and angle determined by spark chambers, and the total hadron energy measured by calorimetry counters in target. Summing the muon and hadron energies gives a first estimate of the incident neutrino energy, sufficient to separate π- and K-decay neutrinos. Time-of-flight measurements and fiducial cuts on the interaction point serve to eliminate cosmic rays and machine-associated muons which penetrate the shield. These are the only potential background sources for neutrino events in the experiment.

The principal neutrino interaction which occurs is

$$\nu_\mu + N \to \mu^- + \text{hadrons},$$

which is the weak-interaction analog of electromagnetic deep-inelastic electron scattering. If a W exists, the analogy is particularly close since the W^+ replaces the photon as the mediator of the interaction. Scaling behavior at the hadron vertex, demonstrated to exist in e-p scattering,[6] is also expected here. This, in fact, has been observed in the lower-energy CERN experiments, which show that to a good approximation $2xF_1(x) = F_2(x)$ and $-xF_3(x) = F_2(x)$, where the scaling variable is $x = -q^2/2M_p\nu$.[7] Here $F_2(x) = \frac{9}{5}F_2^{eN}(x)$, where $F_2^{eN}(x)$ is the structure function measured in e-d inelastic scattering.[8] These are the same scaling functions one obtains from scattering off spin-$\frac{1}{2}$ partons with $V-A$ coupling and no antiparton contributions. We have used these in the discussion of μ^- production below, but our results are quite insensitive to assumptions about the relative sizes of F_1, F_2, and F_3.

If a low-mass W exists, it will manifest itself in two ways: by being directly produced through $\nu + N \to \mu^- + W^+ + N$ [Fig. 1(b)], and by reducing the total cross section through its propagator [Fig. 1(a)]. We have combined both of these effects by looking at the ratio of W production to ordinary neutrino events, using the structure-fuction assumptions stated above.[8]

As a result of this run, 167 neutrino interactions have been identified. This is a clean sample, since background problems are negligible. In order to facilitate the analysis, we have applied geometric fiducial cuts to the data. This

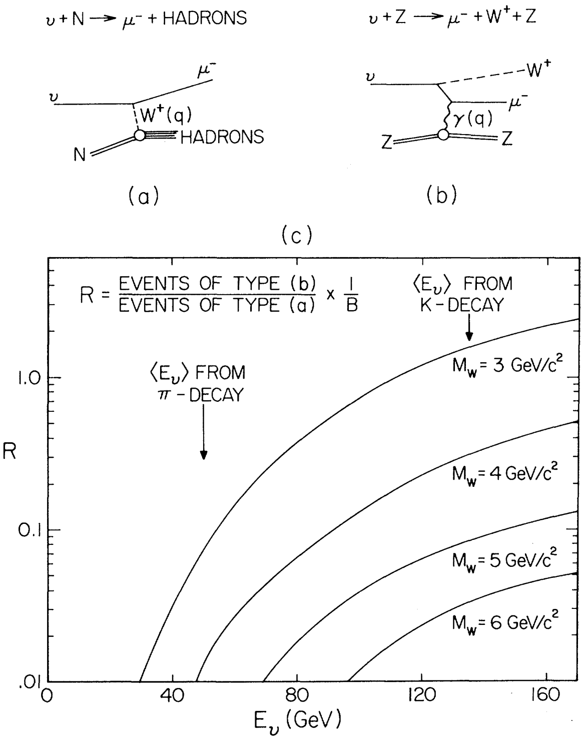

FIG. 1. (a) Deep-inelastic neutrino scattering, mediated by the hypothetical W. (b) W^+ production (a similar diagram with the W-N interaction has been omitted). (c) The predicted ratio of observed events of type (b) to type (a) as a function of neutrino energy and W mass. The detection efficiency of the apparatus, the W^+ production cross section, and the μ^- production cross section with W propagator are all included.

reduced our data sample to 145 events. Also, events that could not be completely reconstructed have been eliminated, further reducing our sample to 112 "analyzable" events. The second class of events eliminated were all identifiable as ordinary neutrino interactions ($\nu_\mu + N \rightarrow \mu^- +$hadrons).

Recall that for W production, we expect a low-energy μ^- produced along with the W boson, and a higher-energy μ^+ from W decay. In our apparatus, we then expect to observe and identify a pair of muons. Typically, only the μ^+ is energetic enough to traverse our toroidal magnet and be selected according to sign.

Analyzing our sample of 112 events, we find *no events* with a pair of muons. In order to simplify the criteria, we have also searched our data for "wrong-sign" muons. We find that only 1 out of 112 events has a μ^+, rather than a μ^-. In other words, asking the simplest possible requirement (the presence of a positive muon) gives

TABLE I. The number of expected $W \rightarrow \mu^+ + \nu$ events expected in our experiment. This has been estimated using the energy spectrum of the sample of 112 ordinary ν events and the information from Fig. 1(c). These rates are given for $B = 1$ and should be scaled accordingly.

M_W (GeV/c^2)	Expected number of W events
3.0	42.
4.0	8.4
5.0	2.1
6.0	0.8

only one potential W candidate. A detailed examination of this event shows visible hadron energy deposition in the calorimeter and *no* evidence for an accompanying μ^-. This event appears to be due to an independently observed antineutrino contamination.

We conclude that there is no evidence for W bosons in our experiment. We are confident in this conclusion, since we could identify the events as not being W bosons so easily.

In order to determine our sensitivity, we have

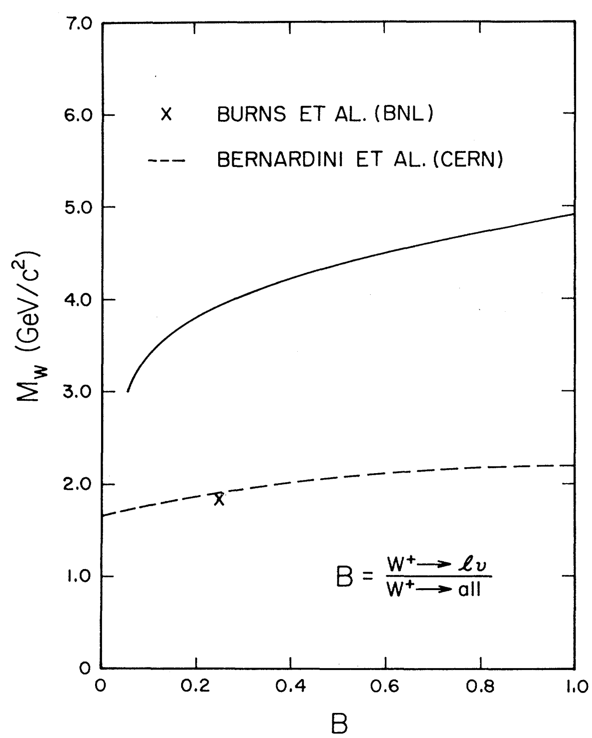

FIG. 2. Upper curve, lower limit (90% confidence level) on the W mass set by this experiment and presented as a function of the decay branching ratio of the W^+ into leptons. Previous limits are also shown.

calculated the event rates for $\nu+N\rightarrow\mu^-+$ hadrons and $\nu+Z\rightarrow\mu^-+W^++Z$ with $W^+\rightarrow\mu^++\nu$ in a Monte Carlo calculation which assumes the following: (1) the scaling functions described above, (2) the effects of a W propagator, (3) calculated W-production cross sections,[9] and the calculated decay distribution for $W^+\rightarrow\mu^++\nu$. Figure 1(c) shows the expected fraction of detected W events in our apparatus as a function of E_ν and M_W.

In our sample of 112 events, there are 18 kaon-neutrino and 94 pion-neutrino interactions. From the energy spectrum of these observed 112 neutrino interactions,[10] we have estimated the expected number of $W\rightarrow\mu^++\nu$ events for our apparatus. This is given for various-mass W bosons in Table I. Our 90% confidence bound as a function of the branching fraction is shown in Fig. 2. For comparison, the previous CERN neutrino limit is also shown.

In summary, we see no evidence for W bosons in this experiment. A lower bound has been set on the mass (i.e., $M_W>4.4$ GeV/c^2 for $B=0.5$) which depends on the branching fraction into leptons. This limit represents a significant improvement over past neutrino results.

We would like especially to acknowledge helpful discussions with J. Smith about W-production cross sections and use of his computer programs. We also appreciate the help and support of the NAL staff, especially Les Oleksiuk and members of the neutrino laboratory.

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Meson-Exchange Corrections to the Cross Section for $n+H^2\rightarrow H^3+\gamma$

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It is shown that agreement between theory and experiment regarding the cross section for radiative neutron-deuteron capture can be achieved by considering the effects of meson-exchange current on the magnetization density of the three-body system. The calculated cross section is 0.52 ± 0.05 mb.

The mesonic currents that mediate the nuclear force distort the free-state electromagnetic properties of nucleons when they are bound in a nuclear system. Taking into account the existence of meson-exchange currents, several investigators have recently eliminated some longstanding discrepancies between theory and experiment that could not otherwise be accounted for. Examples